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# Constituent Quarks, Chiral Symmetry and the Nucleon Spin<sup>1, 2</sup>

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## Abstract

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# Constituent Quarks, Chiral Symmetry and the Nucleon Spin<sup>1, 2</sup>

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**Abstract.** It is argued that the constituent quarks are expected to show a non-trivial spin and flavor structure, due to the anomalous breaking of the chiral symmetry in the U(1) sector.

Deep inelastic scattering reveals that the nucleon is a rather complicated object consisting of an infinite number of quarks, antiquarks and gluons. Although there is only scarce information about the internal structure of the other strongly interacting particles, nobody doubts that the same is true for all mesons and baryons. Nevertheless it seems that under certain circumstances they behave as if they were composed of a single constituent quark and another constituent antiquark or three constituent quarks. Examples are the magnetic moments of the baryons, the spectroscopy of mesons and baryons, the meson-baryon couplings, the ratios of total cross sections like  $\sigma(\pi N)\sigma(NN)$  and so on. Thus it seems to make sense to decompose the proton into three pieces, into three constituent quarks called U or D. A proton would have the composition (UUD). The constituent quarks would carry the internal quantum numbers of the nucleon.

In deep inelastic scattering, one observes that a nucleon has the composition  $|uud\bar{q}q...g...>$  (g: gluon, q = u,d,s), i.e., the quark density functions (which are scale dependent) are described by a valence quark and an essentially infinite number of quark-antiquark pairs. One might be tempted to identify the valence quark, defined by the corresponding quark density function, with a constituent quark. This identification would imply that the three-quark picture denoted above is nothing but a very rough approximation, and both  $\bar{q}q$ -pairs and gluons need to be added to the picture. However, in this case, one would not be able

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to understand why the model of a baryon consisting of three constituent quarks works so well in many circumstances. It seems much more likely to us that a constituent quark is a quasiparticle which has a non-trivial internal structure on its own, i.e., consisting of a valence quark, of many  $\bar{q}q$ -pairs and of gluons – in short, it looks like one third of a proton. Thus a constituent quark has an effective mass, an internal size, and so on. This interpretation of a constituent quark is not new; it was already pointed out about 20 years ago<sup>1</sup>. Nevertheless it is still unclear to what extent it can be derived from the basic laws of QCD, since it is deeply related to non-perturbative aspects of QCD, like the confinement problem. In two dimensions the constituent quarks can be identified with certain soliton solutions of the QCD field equations<sup>2</sup>.

One way to gain deeper insights into the internal structure of the constituent quarks is to consider spin problems, which is the topic of this talk. In the constituent quark picture, it is, of course, assumed that the nucleon spin is provided by the combination of the spins of the three constituent quarks. If the latter have a non-trivial internal structure, the question arises whether also the spin structure of the constituent quarks is a complex phenomenon, as it seems to be for the nucleon, or not.

A simple model for the spin structure would be so assume that the spin of, say, a constituent U-quark is provided by the valence u-quark inside it, and the  $\bar{q}q$ -cloud and the gluonic cloud do not contribute to the spin. We shall conclude that this “naïve” picture does not seem to be correct.

Before we discuss the constituent quarks, let us summarize the results about the spin structure of the proton. As usual we define the distribution functions of the quarks of flavor  $q$  and helicity  $+1/2(-1/2)$  by  $q_+(q_-)$ . The lowest moment of the structure function  $g_1$ , measured in the deep inelastic scattering of polarized leptons off hadronic targets, is given by the moments of these quark densities  $\Delta q$ :

$$\int_0^1 g_1 dx = \frac{1}{2} \left( \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right), \quad (1)$$

$$(\Delta u = \int_0^1 dx (u_+ + u_- + \bar{u}_+ - \bar{u}_-) \text{ etc.}).$$

The spin density moments  $\Delta q$  are determined by the nucleon matrix elements of the associated axial-vector currents ( $s_\mu$ : spin vector):

$$\Delta q \cdot s_\mu = \langle p, s | \bar{q} \gamma_\mu \gamma_5 q | p, s \rangle. \quad (2)$$

The experimental data give<sup>2</sup>:

$$\int_0^1 g_1 dx = 0.114 \pm 0.012 \pm 0.026. \quad (3)$$

The Bjorken sum rule which follows from the algebra of currents in QCD, relates the difference of the  $u/d$ -moments to the axial-vector coupling constant measured in  $\beta$ -decay:

$$\Delta u - \Delta d = g_A \quad (4)$$

(we neglect radiative corrections of the order of  $a_s/\pi$ ). For a recent discussion of the experimental situation see ref. (4). Using  $SU_3$  one finds:

$$g_A = F + D, \Delta u + \Delta d - 2\Delta s = 3F - D. \quad (5)$$

Here  $F$  and  $D$  are defined by the axial-vector matrix elements of the members of the baryon octet. An analysis of the hyperon decays gives:<sup>5</sup>

$$F = 0.47 \pm 0.04 \quad D = 0.81 \pm 0.03$$

$$\Delta u = 0.78 \pm 0.06 \quad \Delta d = -0.48 \pm 0.06 \quad (6)$$

$$\Delta s = -0.19 \pm 0.06$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.10 \pm 0.17.$$

An essential feature of the data is that the “sea” of the  $\bar{s}s$ -pairs in the nucleon appears to be highly polarized; it contributes significantly to the axial singlet charge. This implies that the “Zweig” rule does not seem to work for the matrix elements of the axial baryonic current and can be defined as the axial baryon charge of the nucleon:

$$\Delta\Sigma \cdot s_\mu = \langle p | \bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d + \bar{s}\gamma_\mu\gamma_5 s | p \rangle = \langle p | j_\mu^{05} | p \rangle. \quad (7)$$

In a naïve wave function picture of the nucleon, the axial baryon number corresponds to the portion of the nucleon spin carried by the quarks. Independent of a specific wave function model, we can define  $\Delta\Sigma$  as the relative amount of the nucleon spin carried by the intrinsic spins of the quarks. In the simplest  $SU_6$ -type model of the nucleon, this quantity is one. In reality it may depart significantly from one, due to the contributions of orbital momenta and of the  $\bar{q}q$ -pairs or the gluons to the nucleon spin. Nevertheless it is surprising to observe that  $\Delta\Sigma$  seems to be small compared to one. However, we emphasize that the experiments give solely an information about the axial baryonic charge of the nucleon and not about the spin. Only in a non-relativistic  $SU(6)$  type model, in which the quarks move in an s-wave, the axial baryonic charge and the spin of the nucleon, multiplied by two, are both equal to one. There is no reason why  $\Delta\Sigma$  could not be much less than one, or even zero, if we doubt the validity of the “naïve”  $SU(6)$  model.

Of course, a possible vanishing of the axial-singlet nucleon charge must be discussed in view of the fact that the octet axial charge are, of course, different from zero. Nevertheless

they depart substantially from the values one obtains in a non-relativistic  $SU(6)$  approach, which, for example, predicts  $g_A/g_V = 5/3$ , while in reality one has  $g_A/g_V \approx 1.26$ .

Furthermore the octet charges obey the Goldberger-Treiman relations, which relate the mass of the nucleon and the axial charges to the coupling and decay constants of the pseudoscalar mesons. The latter act as massless Nambu-Goldstone bosons in the chiral limit of QCD<sup>6</sup>. This suggests that also the value of the singlet axial charge is not unrelated to the chiral symmetry of QCD and its dynamical breaking. For this reason it is useful to examine the nucleon matrix element of the axial singlet current in this respect. First we consider it in the chiral limit of  $SU(3)_L \times SU(3)_R$ , in which  $m_u = m_d = m_s = 0$ . In this limit, the octet of axial vector currents is conserved, while the singlet current is not conserved due to the gluonic anomaly:

$$\partial^\mu j_\mu^{i5} = 0 (i = 1, 2, \dots, 8) \quad (8)$$

$$\partial^\mu j_\mu^{05} = 3 \cdot \frac{\alpha_s}{2\pi} \cdot \text{tr} G \tilde{G} = a.$$

It is known that this limit, in which the masses of the three light-quark flavors are neglected, is not far away from the real world of hadrons. In the limit, there exist eight massless pseudoscalar mesons, serving as Goldstone bosons. However, the ninth pseudoscalar, the  $\eta'$ -meson, remains massive and has a mass not far from its physical mass, i.e. about 900 MeV. The axial-vector charges of the baryons are related to the coupling constants of the pseudoscalar mesons with the baryons by the Goldberger-Treiman relations, e.g., those for the pions ( $f_\pi$ : pion decay constant,  $M$ : nucleon mass):

$$2Mg_A = 2f_\pi g_{\pi NN}. \quad (9)$$

We remind the reader how these relations are obtained. The matrix element of the axial-vector current in the octet channel can be described by two form factors:

$$\langle p | j_\mu^{i5} | p' \rangle = \bar{u}(p) \left[ G_1^i(q^2) \gamma_\mu \gamma_5 - G_2^i(q^2) q_\mu \gamma_5 \right] u(p') \quad q = p - p', i = 1, 2, \dots, 8 \quad (10)$$

The induced pseudoscalar form factor  $G_2$  acquires a pole at  $q^2 = 0$ , since the pion mass vanishes in the chiral limit:

$$G_2(q^2) = \frac{2f_\pi g_{\pi NN}}{q^2}. \quad (11)$$

Due to the conservation of the current, one finds  $2M \cdot G_1(0) = 2Mg_A = 2f_\pi \cdot g_{\pi NN}$ . We stress that this relation follows as the result of an interplay between the axial-vector form factors  $G_1$  and  $G_2$ . It is the latter, which contains the pion pole. But the conservation of the current leads to the constraint about  $G_1$ , i.e., to a condition about the axial charge, to

the Goldberger-Treiman relation. In other words, the chiral symmetry allows us to convert a statement about the divergence of the axial-vector current into a statement about the matrix element of the current. Due to the pole in  $G_2$  one finds a non-zero matrix element, even though the current is conserved. In the absence of the pole, the chiral symmetry would be trivially fulfilled; the nucleon mass would have to vanish.

Let us consider the nucleon matrix element of the axial baryonic current in the chiral limit:

$$\langle p | j_\mu^{05} | p' \rangle = \bar{u}(p)(G_1^0 \gamma_\mu \gamma_5 - G_2^0 q_\mu \gamma_5)u(p'). \quad (12)$$

Here the induced pseudoscalar form factor does not have a Goldstone pole at  $q^2 = 0$ . Instead of the Goldberger-Treiman relation, one finds after taking the divergence and setting  $q = 0$ <sup>7,8</sup>:

$$G_1^0(0) = \Delta\Sigma = A(0) \quad (13)$$

where A is the form factor of the anomalous divergence:

$$\langle p | 3 \cdot \frac{\alpha_s}{2\pi} \text{tr} G\tilde{G} | p' \rangle = 2MA(q^2)\bar{u}(p)i\gamma_5 u(p'). \quad (14)$$

We conclude: In the chiral limit of vanishing quark masses, the axial baryonic charge  $\Delta\Sigma$  (“the spin of the nucleon”) is nothing but the nucleon matrix element of the anomalous divergence, i.e., purely gluonic quantity. Not much is known about this quantity. Recently one has succeeded to estimate  $\Delta\Sigma$  by lattice simulations. One finds  $\Delta\Sigma$  to be significantly smaller than unity but not zero ( $\Delta\Sigma \approx 0.2$ )<sup>9,10</sup>.

It is interesting to note the fact that the singlet quantity  $\Delta\Sigma$  is a gluonic quantity while the octet spin densities, e.g.,  $\Delta u + \Delta d - 2\Delta s$ , are determined by the nucleon matrix elements of quark bilinears, this indicates a substantial violation of the “Zweig rule” for the axial-vector nonet. The latter would imply  $\Delta s = 0$ , and we would have  $\Delta\Sigma = \Delta u + \Delta d + \Delta s = \Delta u + \Delta d - 2\Delta s$ . Thus the matrix element of the anomalous divergence, a gluonic quantity, would have to be equal to the matrix element of the eighth component of the axial-vector octet. There is no reason why this should be the case. If it were true, the Ellis-Jaffe sum rule<sup>11</sup> could be used to calculate  $\Delta\Sigma$  in terms of  $g_A$  and the D/F-ratio. The result ( $\Delta\Sigma \approx 0.75$ ) is in disagreement with the experimental results.

We conclude: The violation of the “Zweig rule” in the pseudoscalar channel, which is well known and caused by the QCD anomaly, implies via the mechanism of spontaneous symmetry breaking another violation of this rule for the nucleon- matrix elements of the axial-vector current. The strength of this violation is given by the magnitude of the spin density moment  $\Delta s$ . Therefore it is not surprising that, in particular, this spin density moment appears to be large.

Apparently the violation of the “Zweig rule” is such that the axial singlet charge  $\Delta\Sigma$  is rather small, perhaps even zero. Thus the constituent quark model needs a revision which must take into account this effect, being a consequence of the dynamics of chiral symmetry and its breaking. Below we shall discuss such a revision, which is able to combine both chiral dynamics and the “naïve” constituent quark model<sup>12,13,14</sup>.

First we consider a simplified case, namely the one of QCD with the two flavors  $u$  and  $d$  only. The strange quarks and the “heavy” flavors  $c$ ,  $b$  and  $t$  are disregarded. Furthermore, we assume  $m_u = m_d = 0$ , i.e., the chiral symmetry  $SU(2)_L \times SU(2)_R$  is exactly fulfilled, and the pions are massless.

Due to the QCD anomaly, the singlet pseudoscalar  $\eta$  (quark composition  $(\bar{u}u + \bar{d}d)/\sqrt{2}$ ) has a mass of the order of the nucleon mass  $M$ . The Goldberger-Treiman relation is exactly valid:

$$2M_n g_A = 2F_\pi g_{\pi NN}. \quad (15)$$

In the  $SU(6)$ -type constituent quark model, the axial-vector coupling constant  $g_A$  is given by the nucleon expectation value of the quark-spin operator  $\frac{1}{2}\sigma_z$ :

$$g_A = \langle \sigma_z(u) \rangle - \langle \sigma_z(d) \rangle = 5/3 \quad (16)$$

where one has:

$$\begin{aligned} 1/2\sigma_z(u) &= 2/3 & 1/2\sigma_z(d) &= -1/6, \\ 1/2(\sigma_z(u) + \sigma_z(d)) &= 1/2 (= \text{nucleon spin}). \end{aligned} \quad (17)$$

In reality  $g_A$  is not equal to  $5/3$ , but about 1.26; i.e., the prediction of the “constituent model” is violated by about 24 per cent. This violation can be understood without giving up the simple ideas of the constituent quark model, as an effect due to orbital motions and relativistic effects. Thus in isovector channel, both the chiral dynamics and the constituent quark model do not contradict, but rather supplement each other. This observation encourages us to consider the “constituent quarks” as separate entities. In a “Gedankenexperiment,” we could consider a polarized “constituent quark”  $Q$  ( $Q = U, D$ ) and study its coupling constants. They would also obey a Goldberger-Treiman type relation<sup>15</sup>:

$$2M_q \tilde{g}_A = 2F_\pi g_{\pi QQ} \quad (18)$$

( $M_q$ : constituent quark mass,  $\tilde{g}_A$  axial-vector coupling constant of the constituent quark,  $g_{\pi QQ}$ : pion-quark coupling constant).

Suppose we consider the corresponding matrix elements of the vector and axial-vector

currents and relate them to the various moments of the quark density functions. One finds naïvely:

$$\begin{aligned}
\langle U | \bar{u} \gamma_\mu \gamma_5 u | U \rangle &= p_\mu / M_U = (p_\mu / M_U) \int_0^1 (u_+ + u_- - \bar{u}_+ - \bar{u}_-) dx & (19) \\
\langle U | \bar{d} \gamma_\mu d | U \rangle &= 0 \\
\langle U | \bar{u} \gamma_\mu \gamma_5 u | U \rangle &= s_\mu \cdot \Delta u = s_\mu \cdot \int_0^1 (u_+ + \bar{u}_+ - u_- - \bar{u}_-) dx = s_\mu \cdot 1 \\
\langle U | \bar{d} \gamma_\mu \gamma_5 d | U \rangle &= 0
\end{aligned}$$

( $s_\mu$ : spin vector,  $p_\mu$ : four-momentum, the quark density functions refer to the U-quark and should carry an index  $u$ , which is not explicitly denoted here.) These relations reflect the expectation that in a constituent U-quark the quark density functions must be arranged such that the correct flavor structure is obtained and that its total spin is carried by the u-flavor. The d-flavor is not supposed to contribute to the spin.

We could go further and be more specific about the structure of the quark density functions. The success to the “Zweig” rule relies on the assumption that  $(\bar{q}q)$ -pairs contribute little to the hadronic wave functions. Correspondingly we can consider a limit in which the  $(\bar{q}q)$ -pairs are neglected (“valence quark dominance”). In this limit we find for a U-quark:

$$\begin{aligned}
\bar{u}_+ &= \bar{u}_- = u_- = 0 & (20) \\
d_+ &= d_- = \bar{d}_+ = 0.
\end{aligned}$$

Only the density function  $u_+$  is different from zero. This is easily understood if we consider the free quark model, in which the “constituent quarks” and the “current quarks” are identical, and we have not only the relations (20), but, in addition, the function  $u_+$  is known:  $u_+ = \delta(x - 1)$ .

Thus the essential difference between a “constituent quark” inside a hadron and a free quark lies in the shape of the density functions  $u_+$ . The confinement forces merely cause this function to depart from a  $\delta$ -function and to spread out over the available x-range.

It turns out that the picture of a constituent quark described above is not consistent with the constraints given by the chiral symmetry. In the constituent model, we have  $\Delta d = 0$ . This implies for a U-quark that both the isoscalar and the isovector combinations of the spin density moments are equal to one:  $\Delta u - \Delta d = \Delta u + \Delta d = 1$ .

The isovector part is determined by the pion pole. If the isosinglet  $\eta$ -meson would also be a Goldstone particle, the associated coupling constants would conspire such that the isovector and isoscalar spin density moments would be equal, and the results of the “naïve” constituent model would be obtained. However, due to the QCD anomaly, the isosinglet



spin density function does not receive a Goldstone pole contribution. Instead it is given by the constituent quark matrix element of the anomalous divergence:

$$\Delta u + \Delta d = A$$

$$\langle U | 2 \cdot \frac{\alpha_s}{2\pi} \text{tr} G \tilde{G} | U \rangle = 2M_u A \bar{u} i \gamma_5 u \quad (21)$$

$$\Delta u = (1 + A)/2 \quad \Delta d = (A - 1)/2.$$

There is no dynamical reason why  $A$  should be equal to one. If it were, the spin density moments would indeed reproduce the constituent quark model result. In particular,  $\Delta d$  would vanish. This is not ruled out a priori, but if it were, it would be a miraculous coincidence.

For all other values of  $A$ , the spin density moment  $\Delta d$  does not vanish. We conclude that for  $A \neq 1$  the constituent U quark must contain  $(\bar{q}q)$ -pairs. Thus a violation of the “Zweig rule” is automatically implied. It is interesting that these pairs are generated by the same non-perturbative mechanism due to the gluon anomaly which causes the  $\eta$ -meson to acquire a mass and not to act as a Goldstone particle in the chiral limit of  $SU(2)_L \times SU(2)_R$ .

Intuitively one can understand the violation of the “Zweig rule” discussed above as follows. The chiral dynamics of a “constituent quark” would obey the “Zweig rule” if it were surrounded by a cloud of  $\pi$  and  $\eta$  Goldstone bosons. The Goldstone poles of the axial-vector current matrix elements would imply, via the Goldberger-Treimann relations in the isovector and isoscalar channel, that the matrix elements obey the constraints given by the “Zweig rule” (in particular  $\Delta d = 0$  for a U-quark and so on). However the QCD anomaly causes the  $\eta$ -pole at  $q^2 = 0$  to disappear. As a result the “Goldstone cloud” of a U-quark consists only of  $\pi$ -mesons.

Thus the dynamical structure of the constituent quark is drastically changed. In particular  $(\bar{u}u)$  and  $(\bar{d}d)$  pairs are generated, which modify the spin structure.

We note that these pairs cannot simply be regarded as the pairs inside virtual  $\pi$ -mesons. Their presence is caused by the chiral dynamics, in particular, by the Goldberger-Treimann relations for the axial-vector matrix elements. Their appearance is a non-perturbative phenomenon just like the generation of the  $\eta$ -mass due to the gluonic anomaly.

It is easy to apply similar considerations, as previously for the nucleon to the constituent

quarks. Also for them we should have  $A \approx 0$ , at least to a good approximation. For  $A = 0$  we find for a constituent U-quark that the “Zweig rule” for the density moments is maximally violated:

$$\Delta u = 1/2 \quad \Delta d = -1/2. \quad (22)$$

We can go further and specify the various density moments. If the “Zweig rule” were valid (both  $\pi$  and  $\eta$  Goldstone modes present), we would have

$$\int u_+ dx = 1, \quad u_- = \bar{u}_+ = \bar{u}_- = 0 \quad d_+ = d_- = \bar{d}_+ = \bar{d}_- = 0. \quad (23)$$

Such a constraint which is not invariant under the renormalization group can only be imposed for a particular value of the energy scale  $\mu$ , which is expected to be the characteristic hadronic energy scale. The removal of the  $\eta$  Goldstone pole causes a shift in the density moments, which we can parametrize by two functions  $h_+$  and  $h_-$ :

$$u_+ = u_+^v + h_+ \quad \bar{u}_+ = d_+ = \bar{d}_+ = h_+ \quad (24)$$

$$u_- = \bar{u}_- = d_- = \bar{d}_- = h_-$$

( $u_+^v$ : intrinsic density function of U-quark in the absence of the anomaly,  $\int u_+^v dx = 1$ ). We find for  $A = 0$ :

$$\Delta \Sigma = \Delta u + \Delta d = 1 + 4 \int_0^1 (h_+ - h_-) dx = 0 \quad (25)$$

$$\Delta u - \Delta d = 1$$

$$\int_0^1 (h_+ - h_-) dx = -1/4. \quad (26)$$

We observe that  $\Delta \Sigma$  vanishes, because the constituent U-quark contribution to  $\Delta \Sigma$  is cancelled by the pairs. A cancellation is only possible, if the density function  $h_-$  is different from zero. On the other hand  $h_+$  can be zero, in accordance with the sum rule (26). The simplest model obeying the constraints discussed above is one in which we have

$$\begin{aligned} h_+ &= 0, & \int h_- dx &= 1/4, \\ u_+ &= u_+^v, & \int u_- dx &= \int \bar{u}_- dx = \int d_- dx = \int \bar{d}_- dx = 1/4 \\ & & d_+ &= \bar{d}_+ = \bar{u}_+ = 0. \end{aligned} \quad (27)$$

Thus we obtain in the case  $A = 0$  the following picture of a polarized constituent U-quark in the  $SU(2)_L \times SU(2)_R$  limit: The density function  $u_+$ , which describes the density of u-quarks polarized in the same direction as the U-quark, is unaffected by the QCD anomaly. The latter causes a large violation of the “Zweig rule” in the sense that  $(\bar{q}q)$ -pairs are generated. We shall refer to this “cloud” of  $(\bar{q}q)$ -pairs as the “anomaly cloud”.

The density functions  $u_-, \bar{u}_-, d_-, \bar{d}_-$  are different from zero; i.e., the pairs are polarized opposite to the original constituent quark. The sum of all (anti)-quark spins is zero. Thus for  $A = 0$  the quarks do not contribute to the spin of the constituent quark. The latter is provided either by the orbital angular momentum of the pairs or by gluons or both. This can be seen as follows. If we would turn off the QCD anomaly (e. g. formally by setting  $n_c = \infty$ ), the “naïve” picture should hold, i.e., the spin of the U-quark is carried by the valence quark  $u_v$ . Once the anomaly is introduced, the u-valence quark continues to contribute its spin, but the  $(\bar{q}q)$  pairs cancel the latter. Their total angular momentum must be zero. Otherwise, the introduction of the anomaly would violate the conservation of angular momentum.

Thus we have:

$$\begin{aligned} J_z(U) &= +1/2 = J_z(u_v) + J_z(\text{cloud}) + (L_z(\text{cloud}) + L_z(\text{gluons})) \\ &= +1/2 + (-1/2) + (+1/2). \end{aligned} \quad (28)$$

In the case  $A \neq 0$ , the cancellation between the spin of the valence quark and the spins of the “anomaly cloud” and of the gluons would not be complete, but the sum of the spins and of the orbital angular momenta of the pairs in the “anomaly cloud” would still be zero.

Finally we consider the case of the three-light flavors u,d,s. In the chiral limit of  $SU(3)_L \times SU(3)_R$ , we obtain for a constituent U-quark in analogy to eq. (27):

$$\Delta U = 2/3 \quad \Delta d = -1/3 \quad \Delta s = -1/3. \quad (29)$$

In the symmetry limit, the “anomaly cloud” is, of course,  $SU(3)$  symmetric. In reality symmetry breaking will be present. The result will be that the effects of the  $(\bar{s}s)$  pairs are somewhat reduced compared to those of the  $(\bar{u}u)$  and  $(\bar{d}d)$  pairs. For example, in a U-quark we expect:  $|\Delta d| > |\Delta s|$ . The actual spin density momenta of the U, D constituent quarks will lie between the extreme case of  $SU(2) \times SU(2)$  ( $\Delta d = -1/2$  for a U-quark) and of  $SU(3) \times SU(3)$  ( $\Delta d = -1/3$  for a U-quark).

It has been argued that the anomaly could contribute to the axial-singlet charge if gluons are highly polarized nucleons. In this case their contribution to the singlet charge could be calculated perturbatively<sup>16,17</sup>. In our approach we see no reason for a large gluonic polarization. Thus the effect discussed in ref. (16,17) would be negligible in comparison to the non-perturbative phenomenon discussed here.

The smallness of the axial-singlet charge, parametrized above by the parameter  $A$ , follows also within the Skyrme-type model, as discussed in ref. (18). The connection of this model to the scheme discussed here remains unclear, although some common features exist. In

our approach we would also expect that in the case of one flavor the spin of a constituent quark is cancelled partially or fully by the “anomaly cloud.” Thus we see no qualitative difference between the cases of one or two (three, ...) flavors. On the other hand in the Skyrme model the case of one flavor is not defined.

The picture of “constituent quarks” carrying a polarized “anomaly cloud” described here, implies that many aspects of hadronic physics, especially those in which polarization and spin aspects are relevant, must be reconsidered. Among them are the magnetic moments of the baryons, the polarization phenomena of hyperons in hadronic processes and the spin asymmetries observed in the strong interaction processes. Many further tests of the ideas presented here can be envisaged, once spin asymmetries can be measured in electroweak lepton-hadron reactions at high energies. The generation of a cloud of  $(\bar{q}q)$ -pairs by the QCD anomaly reminds us of the “Cooper pairs” in the BCS-theory of superconductivity. Indeed there are some analogies between superconductivity and hadronic physics in the chiral limit, e.g., the appearance of the mass gap, which in QCD is related to the anomaly as well as to the dynamical breaking of scale invariance and the chiral symmetry, and the presence of pairing forces, which in QCD are responsible for the removal of the Goldstone pole in the singlet axial-vector channel.

According to standard meson dominance ideas, the axial-singlet charge of the nucleon is related to the coupling constants of the neutral  $1^{+-}$ -axial-vector mesons. Since apparently the axial-singlet charge is influenced strongly by the gluon anomaly, we would expect that the coupling constants of the axial-vector mesons and their mass and mixing pattern are also influenced by the gluon anomaly. In particular the mass eigenstates of the axial-vector mesons would show a quark composition similar to the pseudoscalar mesons (where the gluon anomaly plays an essential role) and not similar to the vector mesons (where the mixing between  $\bar{u}u$ ,  $\bar{d}d$  and  $\bar{s}s$  is very small)<sup>19</sup>.

In this lecture, I have described why polarized constituent quarks should be surrounded by a cloud of polarized quark-antiquark pairs. Our reasoning was entirely based on phenomenological arguments. It would be interesting to see how these polarized pairs are generated dynamically, via those non-perturbative effects, due to instantons and the like, which are responsible also for the QCD mass gap and the breaking of the chiral symmetry in the axial-singlet channel. An explicit dynamical model along these lines is not yet available.

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